

# Visual search processing assessed by MEG

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## 1 Introduction

Visual search tasks include two different types of search processing. In one type, a target item is segregated automatically from among the distracters without attentional shifts (pop-out); this has traditionally been called “parallel” processing because reaction time is not affected by set size. In the other type, a target is detected by using attentional shifts; this has been called “serial” search processing because reaction time is prolonged in relation to an increase in set size. For example, an oblique bar among vertical bars is detected faster (parallel) than a vertical bar among oblique bars (serial). Visual search including such an asymmetry has been modeled as “feature integration theory” [1,2].

However, conflicting results have been reported [3-5]. For example, conjunction searches, in which the features of a target differ from those of distractors in more than two categories, were predicted to be “serial” by the theory, but were shown to be “parallel” in some cases. Additionally, it has been pointed out that reaction time also did not indicate a dichotomy of parallel or serial processing. The “guided search model” has been put forward as a convincing theory for these results. This model assumes that parallel processing of each “feature map” is modulated by top-down information about the target identity, and that the modulated information is transmitted to an “attention map”. This information guides attention and helps the search for the target [5].

In a recent study, an electrophysiological correlate of visual search was found by using pop-out stimuli. It was shown that the latency of P3 was prolonged in relation to an increase of the set size in the serial search task [6]. When subjects were presented with pop-out displays taken from various feature categories in random order and were required to respond to a certain target among the others, the posterior N2 component at the temporal and occipital scalp electrodes in the latency range of 175 to 300 ms was observed after P1 component. It was found to be enhanced in the pop-out

conditions including the relevant target, in contrast with that including irrelevant targets [7]. The posterior N2 was also detected in an experiment including a conjunction search, which was considered to be parallel processing accompanied with top-down modulation [8]. These characteristics of posterior N2 were considered to be compatible with the “guided search model”.

However, information processing during visual search is still not clear in terms of brain region. In this study, we used magnetoencephalography (MEG) to measure temporal and spatial neural activity related to visual search processing; consequently, we clarified the disparity between pop-out and non pop-out processing.

## 2 Methods

Ten subjects, five males and five females (27-44 years old), participated in Experiments 1 and 3. Five of the same ten subjects participated in Experiment 2. All subjects had normal or corrected-to-normal visual acuity and a normal visual field. Informed consent was obtained from each of the subjects before the experiments.

Experiment 1 was designed to detect the signal related to pop-out. The task was repeated detection of a target; that is search for an oblique bar among vertical bars (pop-out) or search for a vertical bar among oblique bars (non pop-out). Visual stimuli were projected on a screen located 50 cm away from the subject. Item length and width were 0.5° and 0.1°. The luminance of the item was 83 cd/m<sup>2</sup> and that of the background was 1 cd/m<sup>2</sup>. Both pop-out and non pop-out stimuli consisted of 6x6 square arrays of items arranged in three layers in the central field extending from a fixation point to 4° eccentricity, and the target appeared on the middle layers in the target-present trials. The spatial period of each item was 1.5° in the horizontal direction and 1.0° in the vertical direction with a jitter of 0.4°. These stimuli were presented for 50 ms, and the interval between onsets of successive stimuli varied randomly between 1000 and 1400 ms. Target-present and target-absent trials

occurred in a random order with a probability of 50%, and the sequence of display types was counterbalanced for all subjects.

Experiment 2 was designed to observe the effect of voluntary visual attention. Subjects were required to search for a target item (voluntary visual attention) or judge whether a tone burst appeared or not (relieved voluntary visual attention). These visual and auditory stimuli were presented simultaneously: the same pop-out stimuli as in Experiment 1 and a tone burst at a frequency of 1 kHz (85 dB SPL) for a duration of 50 ms with a probability of 50%. Experiment 3 was designed to clarify the generator sites of magnetic responses. Left and right hemifield displays having 6x3 items, whose other stimulus parameters were the same as those in Experiments 1 and 2, were used to calculate equivalent current dipoles (ECDs). The task was repeated detection of a target as in Experiment 1.

A 148-channel whole head MEG system (Magnes, Biomagnetic Technologies Inc.) was used for recordings. Magnetic signals were sampled at a rate of 678.17 Hz. One hundred epochs were selectively averaged for each condition and filtered with a passband of 1 to 40 Hz. In Experiment 2, magnetic signals without auditory stimuli were used for the data analyses. The epoch duration was 980 ms with a pre-trigger of 250 ms. Major magnetic peaks clearly exceeding signals over the noise level were observed in the following time windows: 90-135 ms (M1), 135-165 ms (M2), 165-220 ms (M3), 220-300 ms (M4), and 300-400 ms (M5). The MEG peak-to-peak amplitude was evaluated by averaging the magnetic signals at three channels and at three sampling points around each peak. The latency having the largest amplitude was used as the peak latency. The MEG amplitudes and peak latencies were tested with repeated-measures analyses of variance (ANOVAs). The analysis factors were the display type (pop-out vs. non pop-out) and target condition (present vs. absent) in Experiment 1, and attention type (voluntary visual attention vs. relieved voluntary visual attention) and target condition (present vs. absent) in Experiment 2. ECDs were calculated with a single dipole algorithm using data at 38 channels, which covered an area of around 20 cm in diameter and included negative and positive peaks in a pair. ECDs were judged as meaningful if they met four criteria: (1) the magnetic waveforms in a pair were clearly reversed in polarity; (2) ECDs lasted stably for more than 10 ms; (3) goodness-of-fit was above 90% for M1 and M2 peaks and 80% for M3, M4,

and M5 peaks; and (4) the 95% confidence volume was less than 1 cm<sup>3</sup>. The estimated dipoles were superimposed on the subjects' magnetic resonance images (MRI) in order to identify the location of neural activity.

### 3 Results

In Experiment 1, the MEG waveforms of all subjects showed five peaks after stimulus onset at mean latencies of  $109.8 \pm 3.8$  ms (M1),  $146.0 \pm 3.2$  ms (M2),  $195.7 \pm 5.5$  ms (M3),  $250.3 \pm 6.7$  ms (M4), and  $333.1 \pm 8.8$  ms (M5). The ANOVA test of the amplitude and latency of these magnetic signals revealed two significant main effects of display type on the M3 and M5 peaks. The M3 amplitude in the pop-out condition was significantly larger than that in the non pop-out condition ( $F(1, 9)=14.9$ ,  $p<0.01$ ) (Fig. 1). In the pop-out condition, the M3 amplitude measured in the target-present trial ( $377.1 \pm 46.0$  fT) was larger than that measured in the target-absent trials ( $335.1 \pm 40.8$  fT). The mean latency of M5 in the pop-out condition (322.1 ms) was shorter than that in the non pop-out condition (344.0 ms), and there was a significant effect between these conditions ( $F(1, 9) = 6.8$ ,  $p<0.05$ ). There were no significant effects related to display type and target condition on the other peak, and there was no significant interaction between display type and target condition for all five peaks.

In Experiment 2, the MEG waveforms produced by pop-out stimuli were similar to those obtained in Experiment 1.

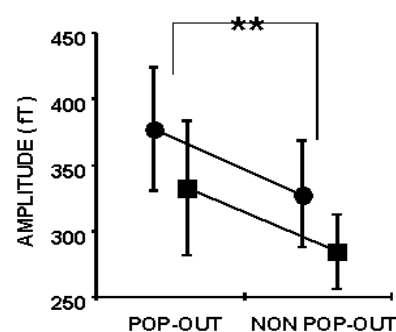


Figure 1: The M3 amplitude produced by the two display types (pop-out vs. non pop-out) and target conditions (present vs. absent). Closed circles and squares denote target-present and absent trials. The error bars represent mean  $\pm$  1 SE. The marks \*\* denote 1 % significance level respectively.

The amplitudes of the M2 and M4 peaks increased during voluntary visual attention (visual task) as compared with relieved voluntary visual attention

(auditory task). Peak amplitudes differed significantly between the two attentional types for M2 ( $F(1, 4) = 21.6, p < 0.01$ ) and M4 ( $F(1, 4) = 20.1, p < 0.01$ ). There was no significant effect of target condition on amplitude of all peaks and also no interactions between attention types and target condition. Peak latency between the two attentional types differed significantly for M1 ( $F(1, 4) = 7.7, p < 0.05$ ) and M4 ( $F(1, 4) = 7.7, p < 0.05$ ) without interaction between attention type and target condition.

In Experiment 3, ECDs for the target-present trial in the pop-out condition were localized in the following regions: calcarine sulcus (CaS) (M1), posterior fusiform gyrus (FuGp) (M2), intraparietal sulcus (IPS) (M3), posterior superior temporal sulcus (STSp) (M3) and CaS (M4). They were obtained in a hemisphere contralateral to the stimulus presentation for the M1, M2, and M4 peaks; however, there was no clear hemispheric lateralization for the M3 peak. For the M5, the criteria used for calculating ECDs were not satisfied (Fig 2 a, b). The M3 consisted of two pairs of positive and negative magnetic fields, one having pair of magnetic fields around the IPS and the other having a pair of magnetic fields around the STSp. In the latter case, the amplitudes measured under the pop-out condition tended to be larger than those measured under the non pop-out condition as well as larger in the target-present trial than in the target-absent trial ( $n=4$ ). In the former case, the amplitudes in the four conditions were similar ( $n=5$ ).

#### 4 Discussion

The ECDs were localized in the CaS and FuGp of the contralateral hemisphere for the M1 and M2 peaks. In these areas, the orientation and shape of items and textures could be processed as an early feature processing [9-13]. The M3 amplitude was significantly enhanced in the pop-out condition, and ECDs of this peak were localized in more than two regions (e.g., STSp and IPS). This suggests that visual information was transmitted from lower visual areas to more than two regions for further processing, and that the activity related to pop-out was modulated in these areas. The M4 peak shows that ECDs were localized again in the occipital visual cortex of the same hemisphere as the early processing. The M5 peak could be related to reaction time for target detection, and this peak might be identical to cognitive response such as the P3 component in a previous study [6].

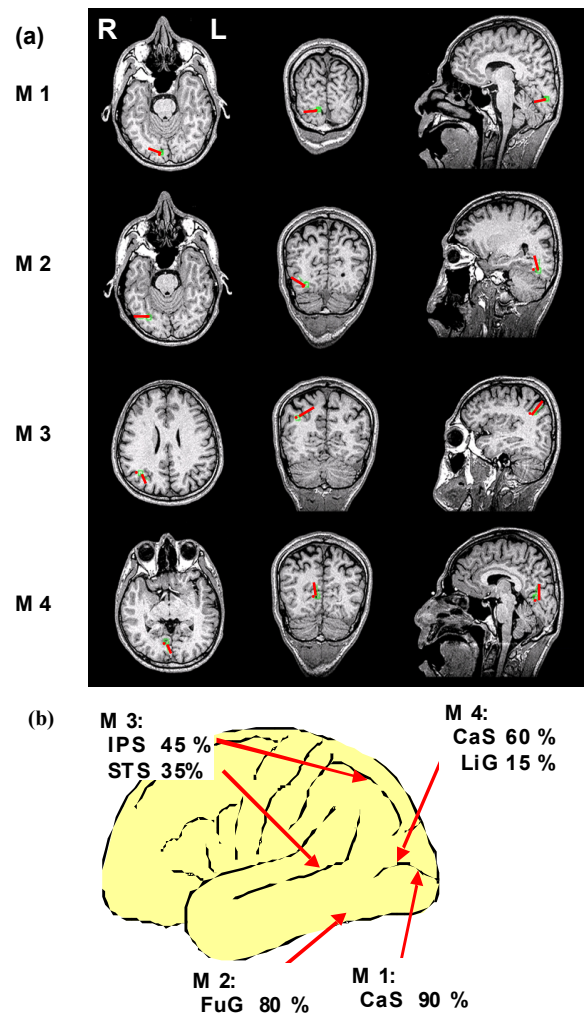


Figure 2: ECDs obtained for one subject (a; left visual field stimulation) and summary for the all subjects (b; left and right visual field stimulation) in the target-present trial of the pop-out condition.

A previous electrophysiological study indicated that the posterior N2 was observed in the temporal and occipital scalp areas at a latency of 175-300 ms [7]. In our experiment, the M3 was detected at a mean latency of 195.7 ms in temporal (STSp) and parietal (IPS) regions, and the M4 was detected at a mean latency of 250.3 ms in the occipital regions. Because of the similarity in latency and dependence on the stimulus conditions, the posterior N2 might have the same sources such as the STSp, IPS, and occipital visual cortex as the present M3 and M4. It has already been discovered that in the striate cortex of the macaque monkey and cat neural activity evoked by a target item differed between the pop-out condition and the non pop-out

condition [14-15]. Therefore, processing specific to pop-out is not considered to be initiated during M3, but rather the processing during M3 may reflect successive processes using pop-out information provided by a lower visual area. The amplitude of magnetic signals around the IPS was high in all display types, while that around the STSp was larger in the pop-out condition. Thus, these areas likely play different roles in visual search; the activation around IPS being dependent on the visual search, while the activation around the STSp being related to the pop-out phenomenon.

In Experiment 2, the effect of voluntary visual attention on M3 peak was not found, whereas the amplitude of M2 and M4 peaks was enhanced when a subject's attention was focused on visual stimuli. Thus, the pop-out process modulating M3 was considered to be automatic from the voluntary visual attention. It could be associated with automatic segregation of a pop-out target without attentional shift. In addition, the attentional modulation shown by the M2 and M4 peaks is compatible with other recent reports obtained with functional MRI in which voluntary visual attention intensified the activation in the visual cortex [16-19], while our result supplements these reports with more detailed temporal information.

Assuming that sequences of magnetic peaks reflect information flow, we can hypothesize that information produced in the occipital visual cortex (M1 and M2) is sent to the IPS and STS, modulated by some automatic processes (M3), and then sent back to the occipital visual cortex (M4). This hypothesis might be supported by the previous anatomical studies, which showed that there are connections from the primary visual cortex to the visual association area, reciprocal connections between the IPS and STS, and backward connections from the IPS (posterior bank) to the inferior temporal cortex, V2, V3, and V4, from these prestriate cortexes to V1, and from the STS to V1 [20-23].

In the "guided search model", which was developed specifically to address the pop-out phenomenon, fundamental visual information, e.g., orientation and color, is processed in parallel on each "feature map". As a result, information in these maps evokes an "attention map" and the target is detected by a serial search on this map [5]. Combining our work with this model, we obtain the idea that the M1 and M2 peaks correspond to parallel feature processing in the occipital visual cortex, and that the M3 and M4 peaks are related to the creation of the "attention map" and the "serial search" on it. If

the "attention map" requires an anatomical basis in processing spatial information, the occipital visual cortex having a retinotopical representation is considered to be a candidate for this map.

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